The Downhole Seismology Project at Parkfield

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Introduction.

In the past 6 months we have moved the MEQ data reduction and our analysis part of the Parkfield Downhole Seismology Project to Duke University, in Durham, NC. Data are continuing to be distributed to UCB and the USGS on a weekly basis, using both a new computer transfer via FTP and Email, as well as the traditional mailing of tapes. In 1991, we have published or have participated in the publishing of the following paper based on data from the project:

1991 Malin, P.E., and M.G. Alvarez. Recent changes in the episodic character of Parkfield microearthquake activity. Manuscript submitted to Science in 4/91.

1991 Ben-Zion, Y., and P.E. Malin. San Andreas fault zone head waves near Parkfield, California. Science, 251, 1592-1594..

1991 Blakeslee, S.N., and P.E. Malin. High-frequency site effects at two Parkfield downhole and surface stations. BSSA, 81, 332-345.

Current Investigations.

Our must recent work has concentrated on the regional distribution of microearthquake moment release near Parkfield. By separating microearthquakes by region, we have observed a location-dependent increase in the rate of cumulative moment (and, by implication, fault slip) near and on the San Andreas fault at Parkfield, CA. The subset of events outside of the Parkfield segment of the San Andreas fault show increased rates of cumulative moment beginning in April 1990. The subset at Parkfield shows the same increase some 4 to 8 months later. Prior to this change and back as far as June 1987, the average cumulative moment rate was nearly constant, except for the occurrence of an M≈4 event in May 1989. Since this event, the cumulative moment rates have increased non-linearly with time. We suggest the data give evidence of a southward diffusing stress front, propagating at a speed of 45 to 90 km/yr.

The region of the Parkfield microearthquake study is shown in Figure 1, along with the epicenters of all the events and the sites of the borehole seismographs used to detect and locate them. Figure 2 shows these events in cross section. Figure 3 shows the cumulative moment of Parkfield events from June 1987 to several months after May 1989, when the M≈4 event took place. This earthquake occurred midway between the 2 southernmost recording sites and at a depth of more than 8 km, a somewhat uncommon location for events of any size. The moments of individual events were calculated by integrating the S-wave displacement and velocity spectra over frequency and assuming that the resulting values fit a frequency-squared model of the earthquake source (5). Summing these moments as a function of time yields the curve in Figure 3, which also shows the least-squares trend line and resulting residuals. (For reasons of scale, the moment of the M≈4 event has been omitted from the figure.)

The trend line and residual moments suggested to us that Parkfield microearthquake activity was being driven by some steady process in which the fault would slip rapidly forward in one period, as evidenced by increased activity, only to lag behind in the next period. It thus seemed possible to anticipate periods of overall increased and decreased seismicity, albeit without reference to any particular location, event size, or precise timing. The M≈4 event occurred in a period when microearthquake activity was lagging behind the average. However this event was not anticipated on the basis of the prior cumulative moment data, as no events of this magnitude took place in the earlier lulls in cumulative moment. A significant departure from this trend began after the first quarter of 1990, and differed by region, as illustrated in Figure 4.

The change in seismic activity can be separated by region, as indicated by the boxes shown in Figures 1 and 2. Boxes 1 and 2 divide the seismicity taking place on the San Andreas fault into northern and southern segments, Box 2 containing the Parkfield segment, Box 1 containing the segment to the north. Box 3 contains all events outside of the Parkfield segment, including Box 1 and the events surrounding but not on the Parkfield segment. We have considered our cumulative moment data in the light of two mechanical models, one for time to failure in rate-dependent material processes (9-11) and a more general one for stress diffusion along rupturing plates (12). In the case of cumulative moment, the former model is given by

$$\Sigma \text{ Moment} = \Delta + \left(\frac{k}{m}\right)(T_f - t)^{-m}$$

where t is time and Δ, K, m, and T_f are constants to be determined from the data. We have used a simplex algorithm (13,16) to fit various subsets of our data with this relation, making use of new cumulative moment data as they came in from the field. Fits to the data before the M≈4 event proved unstable, due apparently to a decreasing rate of cumulative moment in that time period. In terms of the time-to-failure model, this suggests that the data prior to the M≈4 event do not belong to the foreshock sequence of this earthquake; they may perhaps belong to the aftershock sequence of some other event outside our time window (10,11). Fits to the cumulative moments in Boxes 2 and 3 for the time period after the M≈4 earthquake, shown in Figure 4, indicate that events in that time period are also unrelated to the M≈4 event. Moreover, the T_f derived from the Box 2 and Box 3 data sets differ by about a month, and this difference is increasing with the addition of more data. We thus have no confidence that the time-to-failure model applies to the Parkfield area.

Instead, we propose that the cumulative moment data give evidence of a stress diffusion process taking place somewhere below the seismically active region north of Parkfield. Our proposal stems from the observation that the 1990 change in cumulative moment took place first in the north and then some 4 to 8 months later in the south. Since the distance between the centers of the boxes used to separate the regions is about 30 km, the propagation speed of the implied disturbance is on the order of 45 to 90 km/year. Theoretical analysis of stress relaxation below the seismogenic zone indicates that when propagation speeds are reduced to less than 100 to 200 km/year by "barriers" or "asperities" (inhomogeneities in crustal strength), the result is elastic loading of these features (12). The rate of loading would be proportional to the seismicity and the trend of the cumulative moment.

Figure 1.   Map showing locations of the Parkfield borehole seismographs (triangles), the epicenters of 1,856 microearthquakes, and the regions discussed in the text and other figures.   Box 3 includes the events in Box 1.   The westward fanning of events in Box 1 is due in part to the poor station coverage and faster velocities in this region.
Figure 2.   Hypocenters of events in Boxes 1 and 2 projected onto   vertical planes through the zone of highest seismicity in each box.   These planes probably correspond to the San Andreas fault.   The seismicity in Box 2 shows clustering which is not seen in Box 1.   The dashed lines indicate the approximate outlines of the aseismic patches where moderate earthquakes might take place in the future (1).   The recording stations are shown as solid triangles.
Figure 3.   The cumulative moment, trend, and residual of all Parkfield area earthquakes up to and beyond the M≈4 earthquake of 5.89.   The numbers written above the peaks and below the troughs of the residual moments are the number of days between these time points.   The moment of the M≈4 event was removed before least squares fitting of the trend line.
Figure 4.   Cumulative moments by region from 6.87 to the beginning of 3.91.   The moments in Box 3, which includes all events outside of Box 2, show a rapid change in trend in the second quarter of 1990.   A similar change appears to have taken place some 4 to 8 months later in Box 2.   The data in each box have been fit with time-to-failure models, with the respective **Tf** times shown by corresponding vertical lines.

References   and   Notes
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16.   We thank numerous colleagues at the University of California at Berkeley and the United States Geological Survey, with whom we have shared the effort of keeping the Parkfield downhole seismology project alive, and without whose efforts none of the results discussed here would have been possible. We thank G. Lindley of UCSB for use of his simplex curve fitting routine.

Figure 4

Minutes North of 35 Degrees

Depth (Km)

Mag > 1.0
Mag < 1.0
Borehole Station

Cumulative Moment (dynnes-cm)

Year

Cumulative Moment = delta + [K/m (Tf - t)^-m]

M = 4 : 5 / 25 / 89

Box 2

Box 3

Cumulative Moment (dyne-cm)

Time (mo.yr)